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Design and Optimization of Ultrasonic Vibration Mechanism using PZT for Precision Laser Machining

Woo-Jin Kim[1], Fei Lu[1], Sung-Hak Cho[2], Jong-Kweon Park[2], Moon G. Lee[1•]

[1] Department of Mechanical Engr., Ajou University, Republic of Korea; e-mail: kwjwj2@gmail.com
[2] Korea Institute of Machinery and Materials(KIMM), Republic of Korea; e-mail: shcho@kimm.re.kr

Abstract

As the aged population grows around the world, many medical instruments and devices have been developed recently. Among the devices, a drug delivery stent is a medical device which requires precision machining. Conventional drug delivery stent has problems of residual polymer and decoating because the drug is coated on the surface of stent with the polymer. If the drug is impregnated in the micro sized holes on the surface, the problems can be overcome because there is no need to use the polymer anymore. Micro sized holes are generally fabricated by laser machining; however, the fabricated holes do not have a high aspect ratio or a good surface finish. To overcome these problems, we propose a vibration-assisted machining mechanism with PZT (Piezoelectric Transducers) for the fabrication of micro sized holes. If the mechanism vibrates the eyepiece of the laser machining head, the laser spot on the workpiece will vibrate vertically because objective lens in the eyepiece shakes by the mechanism's vibration. According to the former researches, the vibrating frequency over 20 kHz and amplitude over 500 nm are preferable. The vibration mechanism has cylindrical guide, hollowed PZT and supports. In the cylinder, the eyepiece is mounted. The cylindrical guide has upper and low plates and side wall. The shape of plates and side wall are designed to have high resonating frequency and large amplitude of motion. The PZT is also selected to have high actuating force and high speed of motion. The support has symmetrical and rigid configuration. The mechanism secures linear motion of the eyepiece. This research includes sensitivity analysis and design of ultrasonic vibration mechanism. As a result of design, the requirements of high frequency and large amplitude are achieved.

Keywords: Ultrasonic Vibration Mechanism; PZT; Laser Machining; Optimization; Taguchi method

1. Introduction

In recent years, the human lifespan growth stimulates the research and development of medical instruments and devices. In these medical devices, the stent is processed through ultra-precision processing technology, and is used to serve the flow on the blood vessel. The surface of the stent is coated by a mixture of polymer and drug to avoid cloting of blood, however, this polymer remains in the human body and may cause some problems. These problems

Corresponding author: Tel. +82-31-219-2338, Fax. +81-31-219-1611, E-mail: moongulee@ajou.ac.kr

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can be overcomed by impregnating drug in a microsized hole on the surface of the stent, thereby eliminating the use of the polymer in the process. Normally, the microsized holes are achieved through ultra-precision processing technology. However the traditional fabrication method can not get a high aspect ratio or a good surface finishing. In order to overcome these difficulties, we propose to use PZT (Piezoelectric Transducers) mechanism for the fabrication of microsized holes.[1] The proposed mechanism vibrates the eyepiece of laser optics. The ultrasonic vibration through PZT makes laser spot vibrate in a vertical direction, which results in the fabrication of the microsized holes with higher aspect ratio and better surface finishing than those obtained by conventional laser machining. The proposed mechanism has a high frequency and large travel range, therefore, the laser spot vibrates with high frequency and large amplitude. In addition to the abovementioned advantages, the proposed mechanism facilitates high precision and flexibility. It effectively reduces the number of burrs and amount of debris produced during machining. Moreover this mechanism can machine microsized holes in a wide variety of material. In this paper, we will use a finite element analysis method to predict the PZT mechanical device's motion, and analyze the sensitivity of the various design parameters. The analysis reveals the target frequency and a high amplitude.

2. Design of PZT mechanism

2.1 System structure

The proposed machining system is shown in Fig. 1. The most important part of this system is the vibration module, which consists of three units; Ultrasonic vibration guide, PZT actuator and eyepiece. When the system is operating, a laser beam is generated by a laser head, which will pass though a lens and finally reach the workpiece. The PZT actuator used to vibrate the eyepiece in this system is a cylindrical PZT actuator (P-025.10H, Physik Instrument GmbH & Co.). The PZT actuator has a large force, therefore it does not directly connect with the eyepiece so as to avoid deformation. It should be contact with a guide mechanism, which must be designed to have high stiffness and linear motion. Again the ultrasonic vibration guide holds the lens in eyepiece.

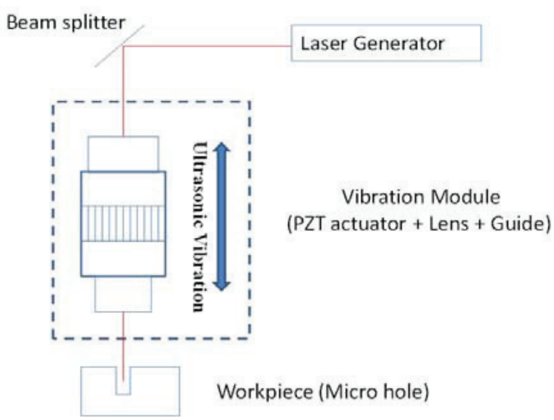


Fig. 1 Schematic diagram of system

2.2Assembly drawing of the PZT mechanism

Fig. 2 shows the proposed ultrasonic vibration mechanism. Due to the large force produced by the PZT actuator, the supports are designed to be rigid enough with solid structure. To vibrate at a high frequency, the support of vibration mechanism is designed to have robustness with reinforcement supports. The PZT is preloaded by a bolt on the top support. On the top and bottom of the PZT, two pieces of ceramic (Al_2O_3, 99.7%) bushings are added to insure no concentrated stress on the mechanism of support and guide. [4] It is designed to have ball contact between the PZT and ceramic instead of face-contact to avoid shear deformation of PZT which may result in fracture. This design is easy to generate parallel motion but not to be over-constrainted when the PZT is moved. The eyepiece embedded in the guide is designed without contact with the PZT directly so that all the force from the PZT actuator transmits to guide, which will protect the eyepiece from damage. The motion of eyepiece and lens will move linearly because of the symmetric structure of the guide. If parasitic motion happened, it will make the position error of the hole during machining. Moreover, it results in incorrect hole size and bad surface finish.

All parts of this mechanism are fastened by bolts so that it will be easy to be assembled and disassembled if some parts need to be redesigned..

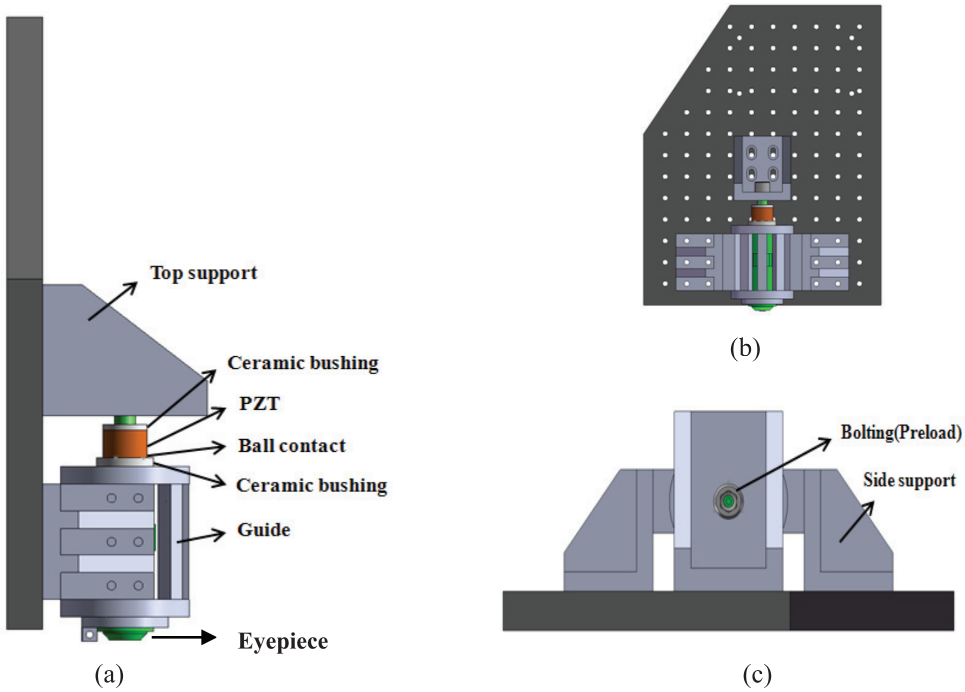


Fig. 2 Assembly mechanism (a) Side View (b) Front View (c) Magnified top view

3. Experiment setup and results

3.1 Experimental Setup

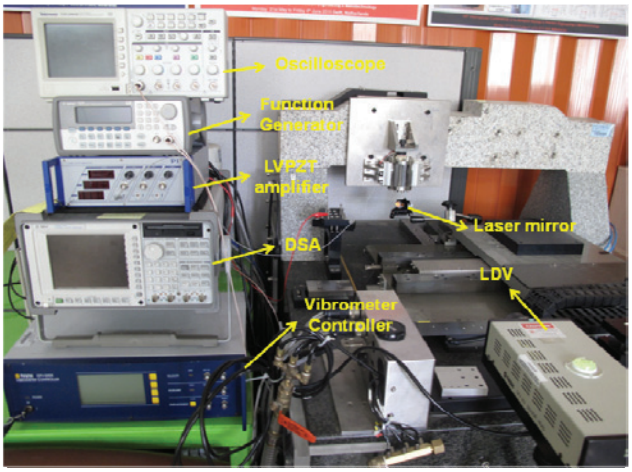
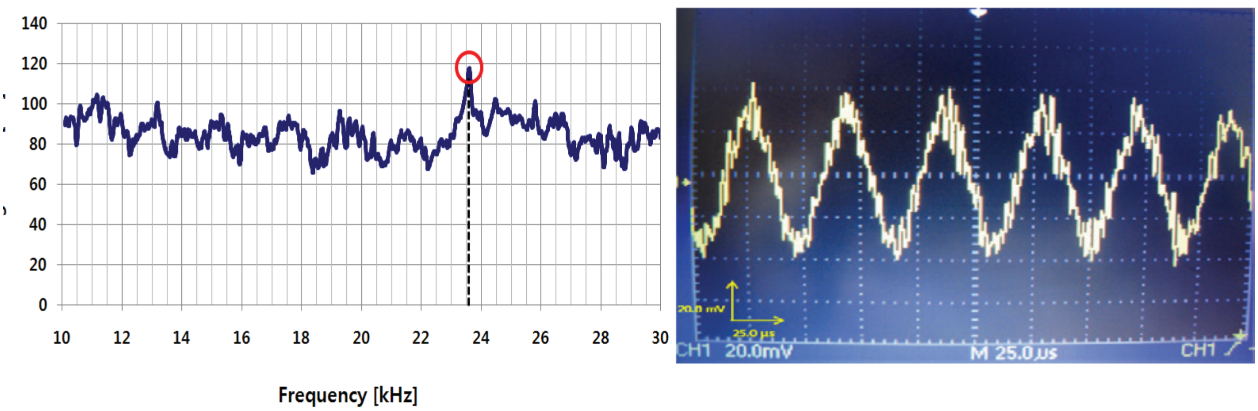


Fig. 3 Photograph of the experiment setup

The experimental setup is shown in Fig. 3. The vibration mechanism is fixed on the granite. The experimental devices are DSA (Dynamic Signal Analyzer, Agilent, 35670A), LVPZT amplifier (Low voltage PZT amplifier, Physik Instrumente GmbH & Co., E-663), LDV (Laser Dopper Vibrometer, Polytec, OFV-5000), Vibrometer Controller (Polytec, OFV-352), Function generator (Agilent, 33220A), Oscilloscope (Tektronix, TDS 2004B) and HeNe laser mirror (CVI, HN-PM-1025-C-45UNP). The LVPZT amplifier excites the PZT. This amplifier inputs the voltage from -2 V to +12 V and outputs the voltage from -20 V to +120 V. The LDV measures the vibration of eyepiece. The resolution is 2 nm and bandwidth is from 0 Hz to 250 kHz. The HeNe laser mirror reflects the laser beam that shoot from LDV to the bottom of eyepiece. The sinusoid voltage to LVPZT is generated from DSA. The measured vibration was analyzed by DSA again.

3.2 Resonant frequency



(a) (b)

Fig. 4 (a) Resonant frequency of vibrating system; (b) Output displacement at resonance frequency

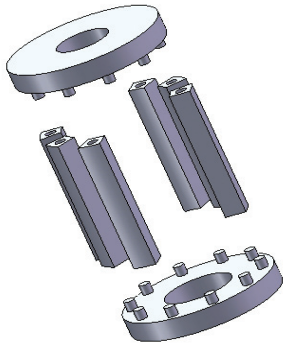
Fig. 4 (a) shows a result of frequency response function (FRF) of test for the vibration mechanism. The range of frequency is from 10 kHz to 30 kHz. The resonating frequency of vibrating system is at the point of red circle. This point is the highest magnitude in this range. It is 23.56 kHz. In other words, we are able to get large travel range at this frequency.

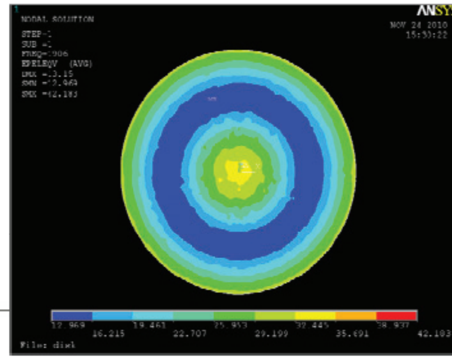
The output displacement at resonance frequency is shown in Figure 4 (b). It is a graph of large travel range for vertical motion of the eyepiece at 23.56 kHz. We set a 23.56 kHz at function generator and the PZT is drived by the voltage at 100 V. A graph of output data was displayed by oscilloscope. The graph shows the amplitude is about 80 mV. The sensitivity of the LDV is 1 μm/V. So we get the travel range at 80 nm. In other words, the large travel range of eyepiece is 80 nm at resonance frequency. If the PZT actuator input the upper voltage at 1000 V, we get the travel range at 800 nm.

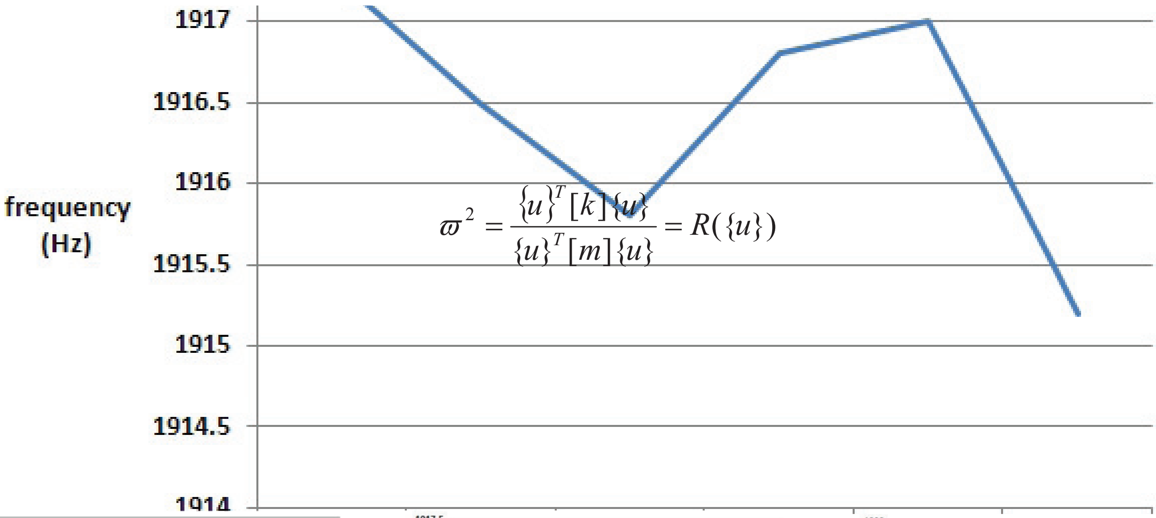
4. Sensitivity Analysis

The vibrating mechanism has high frequency but higher resonating frequency with enough travel is required, therefore an enhanced design is provided using a sensitivity analysis. If the upper and bottom disk are modified, we can satisfy the requirements. The frequency depends on upper and bottom disk's holes number and distance from the center of disk. Especially upper and bottom disk take the PZT vibration directly. The important thing is vertical vibration.

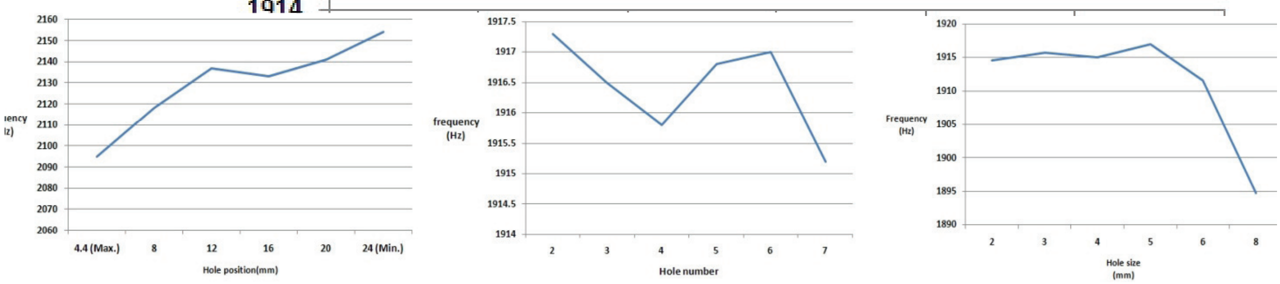
Fig. 5 (a) shows the ultrasonic vibration guide. Fig. 5 (b) shows a strain energy distribution of upper disk. It shows that the biggest strain energy is distributed on the center. There is a small strain energy in the middle. The site has distance from the center site, 24 mm.







$$\varpi^2 = \frac{\{u\}^T[k]\{u\}}{\{u\}^T[m]\{u\}} = R(\{u\})$$



(a) Hole position (b) Hole number (c) Hole size

Fig. 6 Design Enhancement Procedure

Fig. 6 shows first vertical resonance frequency variation by the hole position distance from center, the hole number of 24 mm position and the hole size. The conclusions reached are shown in Table1.

Table 1: Modified Design of Mechanism

Hole position (mm)	Hole number	Hole size (mm)
24	6	5

Hence, we get the final design of disks with the modified parameters. The enhance mechanism's resonating frequency is 21.50kHz and vibrating travel is 3.5μm.

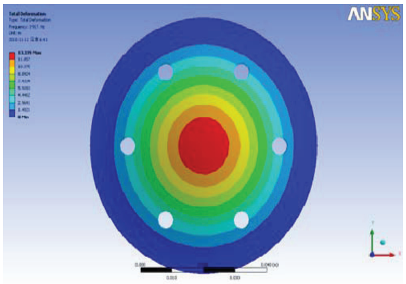


Fig. 7 Result of enhanced design

5. Conclusions

In this paper, an ultrasonic vibration mechanism with the PZT actuator for laser machining is suggested. We find a design which has over 20 kHz of resonating frequency and large vibration travel. To insure the linear motion at a high frequency, the mechanism is designed symmetrically. It uses a cylindrical PZT actuator because the laser beam passes through the center of mechanism. The vibration was measured by DSA, LDV and etc. The resonant frequency of vibrating system is 23.56 kHz. And the large travel range of eyepiece is 80 nm at resonance frequency. To input the max voltage at 1000 V, we get the max travel range at 800 nm. The result will be different with the analysis of experiment. The enhanced design is provided using a sensitivity analysis. Enhancement of the mechanism is based on Rayleigh's quotient. To find higher resonant frequency, we could get rid of mass which is in low strain energy.

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